Fluid mechanics of turbomachines: a review

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Future development of more efficient turbomachinery depends on improving understanding of the fluid mechanics. This paper reviews advances made in the last five years in calculation methods for steady flow, unsteady flows and stability, and instrumentation and its applications. Fundamental problems which need further study are also indicated

Key words: *turbines, fluid mechanics, unsteady flows*

Recent developments in the understanding of the fluid mechanics of turbomachines may be discussed under three main headings:

- calculation methods for steady flow
- unsteady flows and stability
- experimental work, including instrumentation.

The advances made prior to 1977 have been described in a number of reviews published in the early and mid-1970's, examples being the papers of Horlock and Perkins[1], Japikse[2], Marsh[3] and Horlock[4]. Horlock and Perkins reviewed the methods available for calculating the inviscid flow in turbomachines, drawing attention to the matrix through-flow (mtf) and streamline curvature (slc) methods, and then described methods for estimating the growth of the annulus wall boundary layers. Japikse undertook a similar review. Marsh drew attention to the similarities between the mtf and slc methods of analysing turbomachinery flows, showing that these two methods of flow calculation start from the same mathematical formulation of the flow and that they differ only in the method used for solving the governing equations. This unified approach brought together the two main methods of analysis which had been developed in the mid-1960's. Horlock's separate later review concentrated on the developments in the analysis of secondary flows. This paper follows on from these earlier reviews, concentrating on the developments in the past five years.

Calculation methods

At the time of the reviews by Horlock and Perkins and by Japikse, it was generally accepted that the two main calculation methods for inviscid flows, mtf and slc, were based on calculations of the flow on two sets of intersecting surfaces: the cascade or blade-to-blade stream surfaces, *S1*, and the through-flow surfaces between the blades, *S2*. This was the basic concept first developed by Wu[5] who suggested that in a steady flow, the full three dimensional flow pattern might be obtained by iterating between flow calculations for the flow on each set of surfaces. This might be a feasible approach for the flow through a cascade of blades, or an isolated rotor row, but when another blade row is present, the interaction between the blade rows introduces a time variation to the flow.

Flow calculation methods are available for steady flow in cascades and for steady flow on the through-flow stream surfaces. In the multi-stage machine, the through-flow calculation methods, mtf and slc, have relied on treating the flow as steady, this being achieved implicitly by some form of circumferential averaging at inlet to each blade row. To deal with the complex unsteady three-dimensional flow in a multi-stage turbomachine, it will be necessary to move away from the methods for steady two-dimensional flow on a surface and develop new methods for unsteady three-dimensional flow. The time and cost of computation may restrict the pace of this development.

The mtf and slc method of analysis were developed initially for subsonic inviscid flows and some disquiet had been expressed about the inclusion of a loss model in a method for calculating inviscid flows. There was an obvious inconsistency in that a loss model had been combined with the equations governing a loss-free flow. Horlock[6] proposed a simple model in which a dissipative force opposed the velocity vector. Bosman and Marsh[7] showed that this concept of a dissipative force could be included in a more general approach to the mtf analysis to give a 'consistent loss model'. This more general and consistent approach did not require new computer programs, but could be achieved by a simple modification to the existing mtf programs. More recently, Gunton[8] has shown how this consistent loss model can be included in the slc method.

Attention has also been directed at the validity of the flow calculations when the relative flow at entry to a blade row is supersonic, though the axial flow is subsonic. A discussion of this problem is given by Horlock and Grainger[9] who developed an actuator disc method showing how the three-dimensional methods of analysis should be modified when the entry flow is supersonic. For a compressor

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row in the 'fully started' condition, control of the flow rate is exerted by the leading edge geometry. However, a difficulty is that the imposition of a particular entry angle, the 'unique incidence' condition, is generally based on two-dimensional analysis in the blade-to-blade plane of a linear cascade, developed from the original ideas of Kantrowitz[10] and discussed in more detail by Starken[11]. In the 'unstarted' condition, ie if the back pressure is too high or the downstream throat too small, supersonic rows operate with slightly detached shocks and control of the flow angle is not imposed at the leading edge. The slc and mtf methods must then allow for a rapid change of angle and loss increase, by the use of closely spaced calculating stations inside and outside the blade rows. This may adversely affect the local stability of the flow calculations.

At the time of the earlier reviews, there were several methods becoming available for calculating fully three-dimensional flows. The first, which surprisingly has not been used widely, was developed by Stuart and Hetherington[12] and required an iterative solution of the continuity and momentum equations in general curvilinear coordinates. The authors applied their new technique to the flow in a bend and flow in a linear cascade. Carrick[13] found stability and convergence were relatively straight forward and extended the method to include simple viscous loss models, while Barber and Langston[14] drew attention to the problem of specifying the downstream flow condition in three-dimensional flows.

Spalding's methods[15–17] for calculating duct flows appear to be extremely successful both in stationary ducts and in simple rotating channels. The continuity equation and three momentum equations are transformed into finite difference equations by integration over a small localised volume. Two finite difference equations are also used for the turbulent length scale and kinetic energy. In the earlier 'parabolic' method[15], an averaged pressure distribution, p, in the mainstream direction, is decoupled from the momentum equations which are solved for velocity distributions, with subsequent corrections. In the later 'partially parabolic' method[16,17], p is not used and the actual pressure is stored in a three-dimensional array. Velocity components and turbulence parameters, stored in two-dimensional arrays, are evaluated over the cross-stream planes encountered by marching in the mainstream direction. The pressure field is then up-dated by removing the errors in the continuity and momentum equations.

Essentially, the parabolic and partially parabolic methods imply that the 'elliptic effects' are transmitted through the pressure field. Dodge[18] follows a similar approach, splitting the Navier–Stokes equations into an elliptic irrotational potential field component, solved by relaxation, and a rotational component solved by marching downstream. McDonald and Briley[19] adopt a similar approach. Moore and Moore[20] solve the problem in a succession of steps of increasing complexity: inviscid flow with uniform inlet velocity, inviscid irrotational flow and finally viscous irrotational flow. These methods developed by Spalding and other workers have not been widely used in turbomachinery flow problems to date. They appear to work well in duct flows with an accurate specification of the downstream boundary conditions on pressure.

Finite element methods have long been available for a range of problems in solid mechanics and have now been developed to deal with some situations in fluid mechanics. Two-dimensional cascade flows have been studied by Thompson[21] and Grant[22] and a through-flow method was developed by Hirsch and Warzee[23]. Three-dimensional inviscid flows have been solved by at least one industrial research group using finite element methods, but these results have not yet been made generally available. The finite element method is another approach to flow calculations which has not yet received wide acclamation in turbomachinery work. Wider use of the finite element method may depend on being able to demonstrate that it has significant advantages and can deal with more complex flow problems than the existing well-established methods.

Undoubtedly the most successful of the new methods of calculating turbomachinery flows has been the time marching method, which in the early 1970's had been developed by MacCormack[24] and McDonald[25] to study the flow in cascades. A fundamental study of the limitations of the method had been undertaken by Marsh and Merryweather[26] who developed several stable schemes of computation and calculated the flow in a two-dimensional convergent–divergent nozzle. In the early 1970's, the main obstacle to progress in time marching methods was that the time of computation was excessive. In the Marsh and Merryweather approach, this slow convergence to the steady state flow may have been the result of attempting to model the development of the real flow with time. The alternative approach is to regard time marching as a mathematical technique for moving towards the steady state flow from any set of initial conditions, without necessarily modelling the development of the real flow with time.

Denton[27] transformed time marching into a practical economic method for calculating subsonic and supersonic flows in two and three-dimensions. The original hexagonal control element used by McDonald for two-dimensional flow is shown in Fig. 1(a), while Fig. 1(b) shows the new 'Denton' element used for three-dimensional flows. Denton not only speeded up the method of computation, but he applied his method most successfully to cascade flows in two and three dimensions[28]. Two illustrations of the Denton time marching approach are given in Figs 2 and 3. Fig 2 gives the results of a full three-dimensional calculation of flow in a turbine nozzle row. The Mach number distributions on the pressure and suction surfaces of the blades at the tip and hub are shown in Figs 2(a) and 2(b) respectively. Fig 3 shows a second example in which Horlock's[29] solution to the flow through a fully choked closely spaced row is compared with a time marching solution by Singh and Whitfield[30] who used a development of Denton's method. For the latter example, it appears that the analytical solution

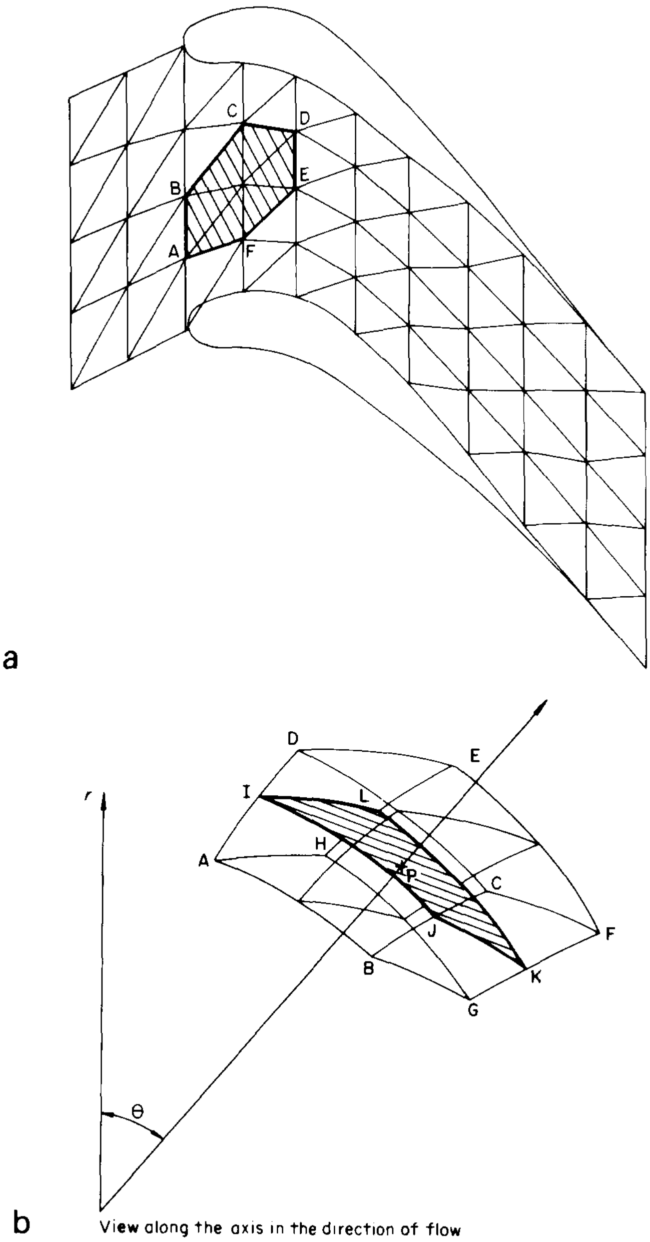


Fig 1(a) Hexagonal elements used by McDonald[25] *(b) details of Denton's 3-dimensional element*

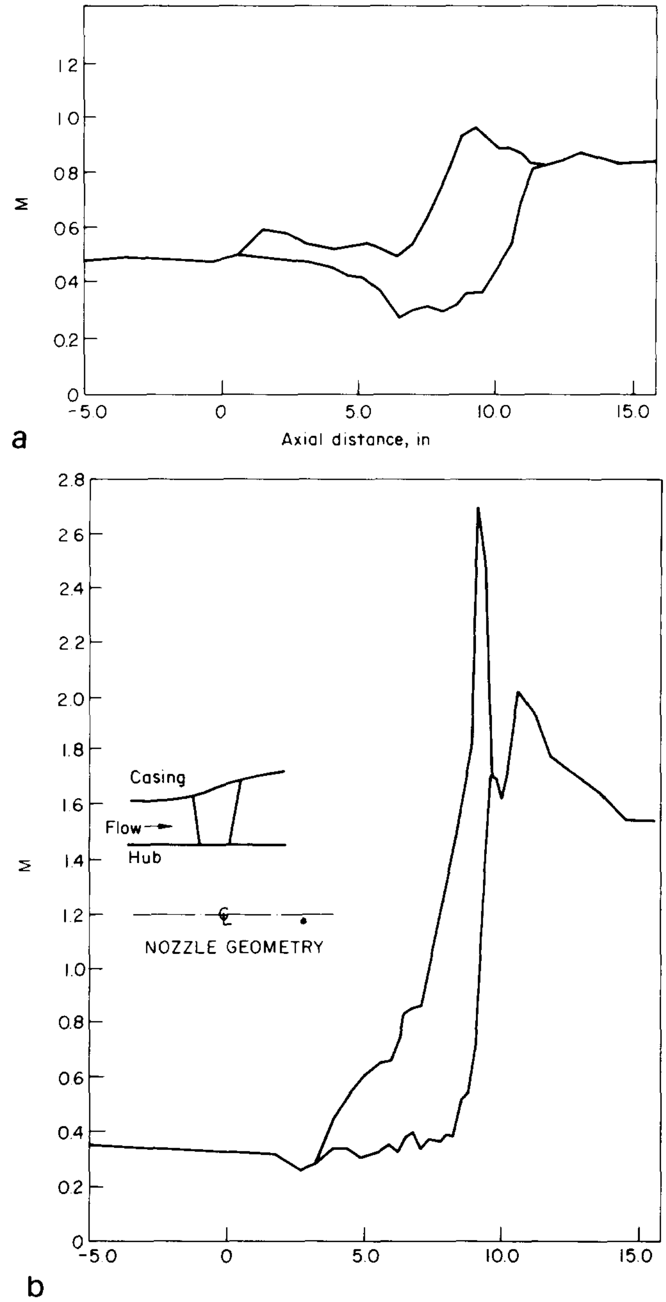


Fig 2 Mach number (a) on the casing stream surface (b) on the hub[28]

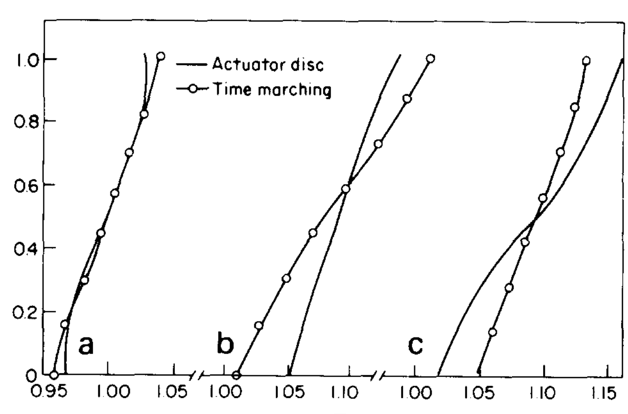


Fig 3 Flow through blade row of varying throat area (a) leading edge (b) trailing edge (c) far downstream

derived by Horlock is in error downstream of the row due to under-estimation of the local shock losses, which are more accurately predicted in the time marching method.

A recent development has been the time marching through-flow method of Spurr[31] which has been used to calculate the flow in nozzles, a single stage turbine, and multi-stage machines. Spurr has compared the results with those for the slc method and has concluded that time marching is far more versatile when dealing with transonic flows. Spurr has also shown[31] that a good estimate of the three dimensional flow can be obtained by iterating between two time marching programs, one for the through-flow and the other for the blade-to-blade flow. The convergence of this technique is extremely rapid, but it does rely on the blade-to-blade surface being approximated by a surface of revolution and the governing equations include no losses other than those which occur at shocks. Spurr has shown that this iterative method leads to flows which are in close agreement with those obtained from a full three-dimensional flow calculation for a transonic annular cascade (Fig 4).

Several workers have attempted to include viscous losses into a flow calculation method, one example being the paper by Bosman and Highton[32]. An interesting development is the work of Torres[33] who has used a time marching method to calculate inviscid, viscous and heat conducting flows in a two dimensional convergent-divergent nozzle. When comparing the predictions with experimental results, Torres has found that the inclusion of the viscous effects leads to better agreement with the experiment, particularly in the location of the shock. The inclusion of a loss model is an essential development for the time marching method if reliable results are to be obtained for multi-stage machines. The present inviscid method may give satisfactory results for a single-blade row, or single stage, where the losses are small, but in a multi-stage machine, the losses are cumulative and a reliable loss model is required.

The separate calculation of the annulus wall boundary layers has not developed much further since the work of Mellor and Wood[34] and Horlock and Perkins[1], although Hirsch[35] has introduced a more complex form of calculation based on Mellor's earlier analysis. Critical in these two approaches is the assumption of the form of the 'defect force' through the boundary layer. Papaillou[36] has made a comparative study of the Mellor and Horlock methods, while Carrick[13] and Linday[37] have taken Horlock's calculation further by incorporating the cross flow (secondary flow) into the boundary layer calculations. However, this degree of complication does not appear to be justified for it is difficult to progress the calculation through a highly cambered blade row. The simple equations for the 'axial' boundary layer thickness, originally proposed by Stratford and later developed by Horlock and Perkins, appear to give reasonably reliable estimates for the blockage produced by the wall boundary layers in turbomachines, this being the information required to correct the mtf and slc calculation methods.

Some attempts have been made to use the mtf or slc methods in conjunction with secondary flow, viscous or boundary layer calculations. Goulas and Baker[38] and Resnich and Goulas[39] have extended the mtf technique for centrifugal compressors by calculating the flow on several meridional stream surfaces. They then apply the analysis given by Lakshminarayana and Horlock[40] to estimate the development of secondary vorticity (in rotating coordinates) along each of the stream surfaces and calculate the resulting secondary flow. Turbulence effects have also been included. A sophisticated approach has recently been introduced by Smith[41] who has used his well-established slc calculation, together with estimates of the boundary layer thickness at the annulus walls. The analysis allows for secondary vorticity and for shed vorticity from the tip clearance region, using the simple model developed by Lakshminarayana and Horlock. Smith then calculates the overall secondary flow in the blade passages due to the total streamwise vorticity and the displacement of the total pressure contours, allowing for diffusion effects. This yields estimates of the radial flows into and out of the annulus wall boundary layers and flow outlet angles which are in good agreement with experiments.

To summarise the position on calculation methods for steady flow, relatively few steps forward have been made in the basic slc and mtf analyses, although several promising efforts have been made to include a consistent loss model and to incorporate boundary layer and secondary flow analyses. Several

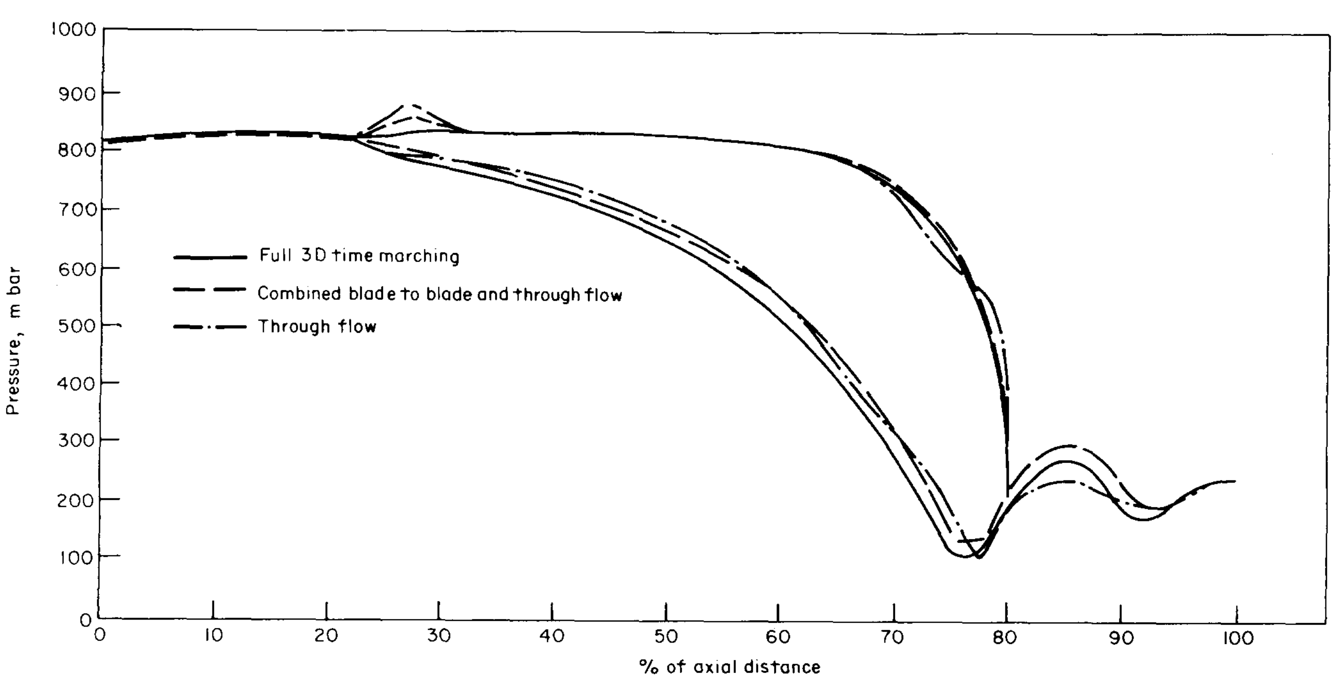


Fig 4 Blade surface pressure distribution at hub[31]

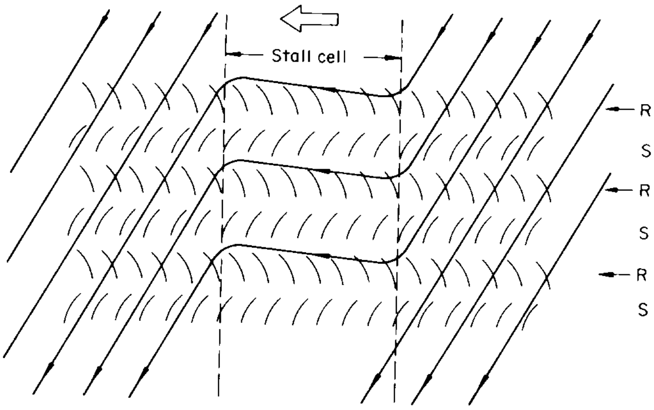


Fig 5 Stall cell structure in absolute reference frame

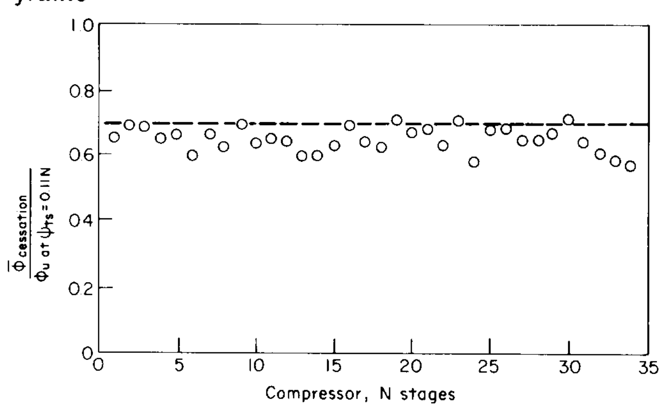


Fig 6 Correlation for $\bar{\phi}$ at cessation of full span stall[43]

alternative methods of flow calculation have been developed and time marching has come through as the main new technique which will be widely used, subject to the limitations on computer time and cost and the incorporation of a satisfactory loss model.

Stability calculations

Major advances have been made in the general area of stability analysis of axial flow compressor performance, and the link with rotating stall. An excellent and wide-ranging review of the stability of pumping systems has been undertaken by Grietzer in his 1980 Freeman Scholarship Lecture for the American Society of Mechanical Engineers. A detailed review is not, therefore, undertaken here, but reference is made to the most significant of recent work, that by Day and Cumpsty[42], and by Day, Greitzer and Cumpsty[43].

Day and Cumpsty used ensemble averaging techniques (see below) to measure detailed properties within stall cells in a multi-stage low speed compressor. The description they give of flow through a stall cell (not past it) is shown in Fig 5; the flow has zero axial velocity in the cell, but tangential velocity approximately equal to the blade speed. Violent deceleration and acceleration takes place at the edges of the cell. Using this description, Day, Greitzer and Cumpsty develop a correlation to predict stalled flow performance. They use two experimental observations, that the non-dimensional 'inlet total to exit static' pressure rise in rotating stall is roughly constant ($\psi_{TS} = 0.11$ per stage) and that there is a critical value of blockage (about 30%) below which stall over the full blade span cannot exist. They deduce that the ratio of flow coefficient at stall cessation ($\phi_{cessation}$) to that in unstalled flow at $\psi = 0.11$ ($\phi_{u at 0.11}$) is very closely equal to 0.7 for all compressor stages or multi-stage low speed compressors (Fig 6). Further they show that the design value of flow coefficient ϕ^* is the dominant factor controlling stall performance. Fig 7 shows the effect of ϕ^* on stall/unstall hysteresis. The reader is referred to the Freeman Scholarship Lecture for further information on recent work on stability.

Experimental work and instrumentation

We shall not attempt to review here recent practical achievements in component design, eg performance characteristics of highly loaded turbines or very high speed compressors. Rather we concentrate on the remarkable developments in instrumentation which have given a new view of turbomachinery flows and a new impetus to analytical studies.

The development of optical instrumentation, and in particular of laser anemometry, has undoubtedly been the most outstanding work; an excellent review paper is that by Weyer[44]. Here we simply note some of the remarkable results obtained, eg the work of McDonald, Bolt, Dunker and Weyer[45], in which a comparison is made of the measured flow distributions in a transonic compressor rotor and a sophisticated computer program which iterates between an slc through-flow method and a time marching blade-to-blade calculation. Fig 8 illustrates calculations and measurements of a rotor mid-span section; the shock structure is clearly represented.

Another major step forward in instrumentation has been the development of phase lock averaging (see Gostelow[46]) in which transient flows are first measured instantaneously, either with pressure transducers or hot wire instrumentation, over many cycles but each triggered from some particular occur-

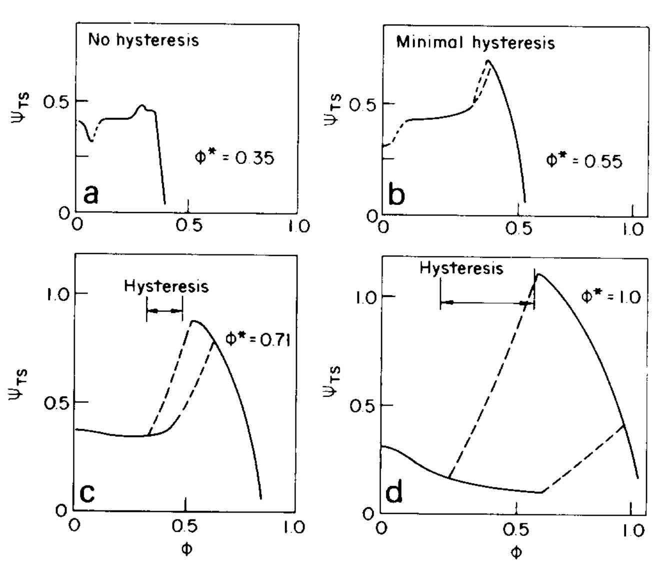


Fig 7 Effect of $\bar{\phi}^*$ (design) on stall/unstall hysteresis

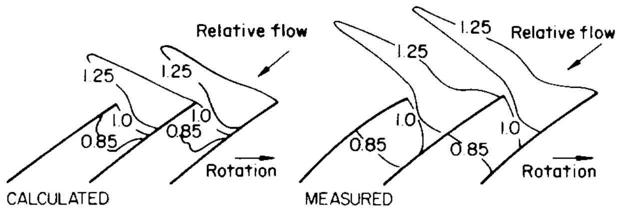


Fig 8 Fan Mach number contours at 68% span and peak efficiency

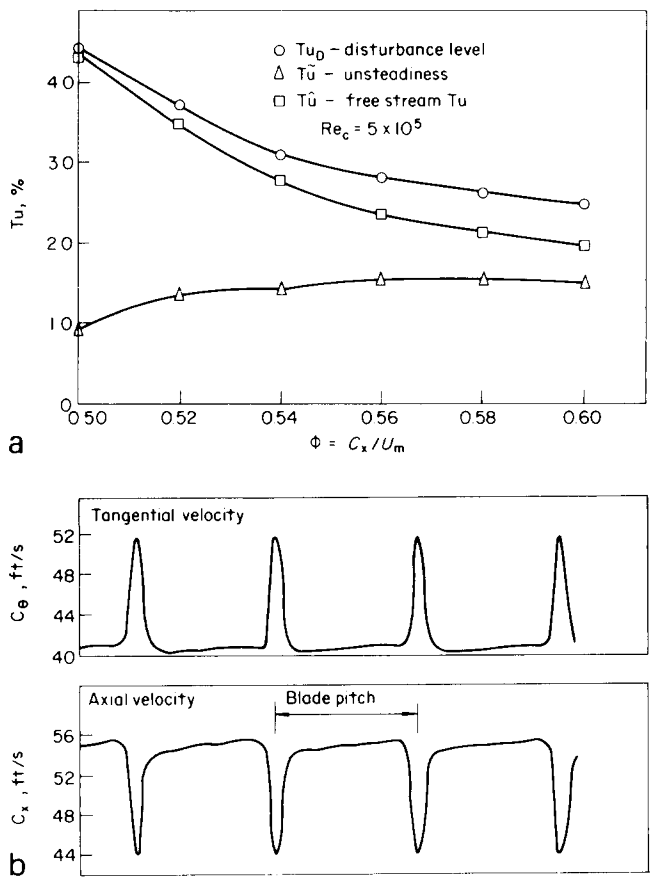


Fig 9 (a) Turbulence and unsteadiness measurements in a compressor[47] (b) ensemble averaged axial and tangential velocities[47]

rence such as passing of a blade or arrival of a stall cell. The flow parameters are then averaged over many cycles at particular instants of time. In this way Evans[47] has separated the ordered unsteadiness due to blade passing from the random unsteadiness or turbulence. Fig 9 shows some of Evans' results. Railly[48] has used the phase-lock averaging technique to make a more careful study of stall cell propagation, triggering the pulse from the arrival of the stall cell. In this way he has been able to measure total pressure losses and angles at points within the stall cell and has produced a remarkable graph (Fig 10) of instantaneous pressure loss against instantaneous incidence. Fig 10 is based upon a particular selected time delay between change of incidence and total pressure loss response, that delay which gives a unique curve.

A third major step forward has been the development of instrumentation within rotating rows, in particular the work of Lakshminarayana and his colleagues at Pennsylvania State University, which has enabled a clear picture of the detailed flows in a rotating system to be obtained. Fig 11 shows an example of turbulence correlation measurements within the rotor of a rocket pump inducer.

More generally, improved instrumentation has enabled better visualization of the detailed three-dimensional flows in turbomachines and cascades (eg the study of flow in turbine cascades by Langston at Pratt & Whitney[49] and Carrick at Cambridge[13]). Several detailed measurements of these flows are described in the proceedings of the Agard Conference held in 1977[50]. There is little new instrumentation involved, but the careful detailed work and new forms of presentation have led to a better understanding of these flows, (eg the observation of the saddle points as originally found by Langston and confirmed by Carrick). Fig 12 gives a three-dimensional presentation of the three-dimensional cascade flow observed by Carrick.

Another major new development is the development of radio telemetry in rotating engines. This is probably of more importance to the analysis of a mechanical failure rather than the detailed fluid mechanics.

A major reference source for new forms of instrumentation in turbomachines is the book edited for the ASME by Lakshminarayana and Rundstadler[51], which contains Weyer's paper on optical instrumentation and accounts of many new developments.

Conclusions

In summary, it would appear that the major new impetus in turbomachinery research in the past few years has come from:

- the development of time marching methods of flow calculation
- an improved understanding of compressor instability
- developments in instrumentation.

The time marching technique is a highly versatile method of calculation which, given sufficient computer time, can provide realistic solutions for invis-

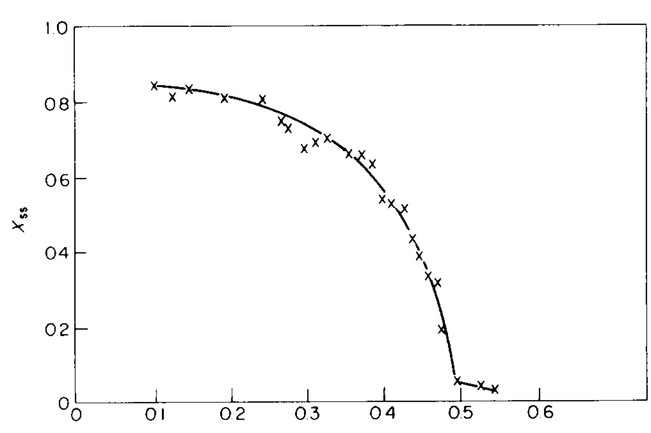
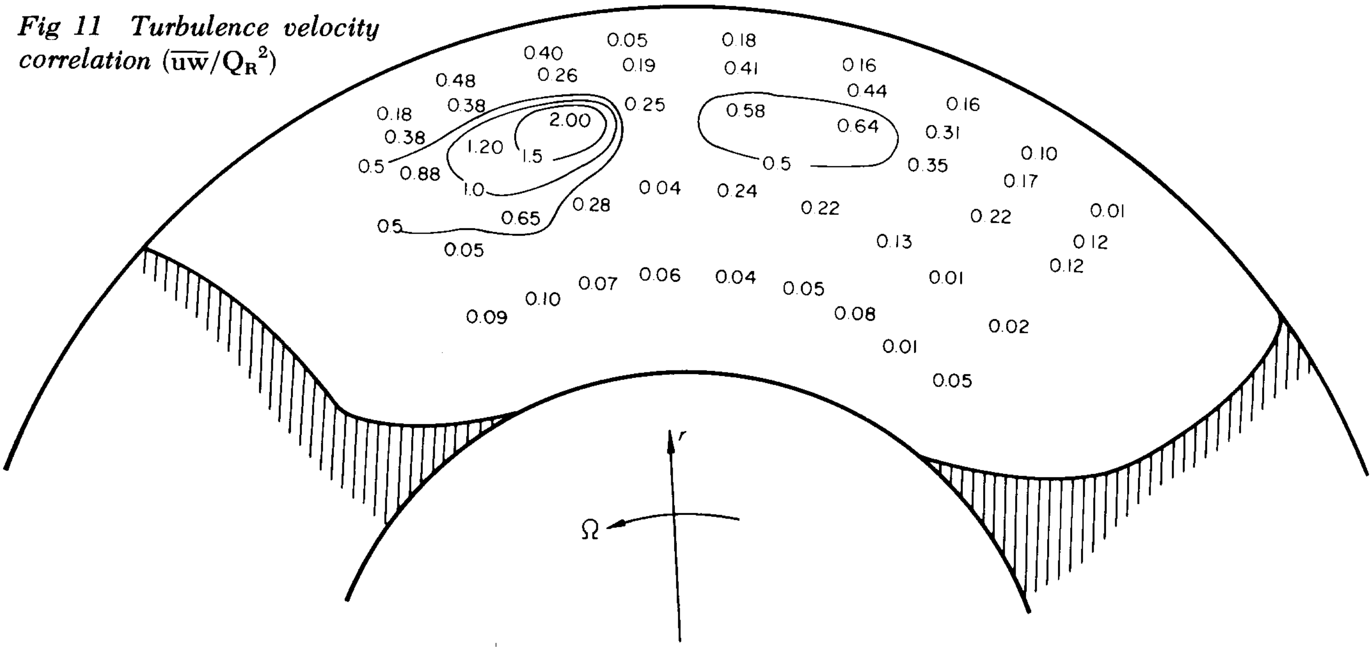


Fig 10 Steady state total head loss characteristic[48]

cid compressible flow with shocks. For the multistage turbomachine, reliable predictions of the flow will depend on including a satisfactory loss model in the time marching method.

The developments in instrumentation are leading to a better understanding of both steady and unsteady flows. For example, recent work on centrifugal compressors has clearly illustrated the nature of separation on the casing walls (ie in the meridional plane) and has thrown some doubt on the jet-wake model of flow in the blade-to-blade stream surfaces of the impeller. It is this kind of experimental dis-

Fig 11 Turbulence velocity correlation ($\overline{uw}/Q_R^2$)



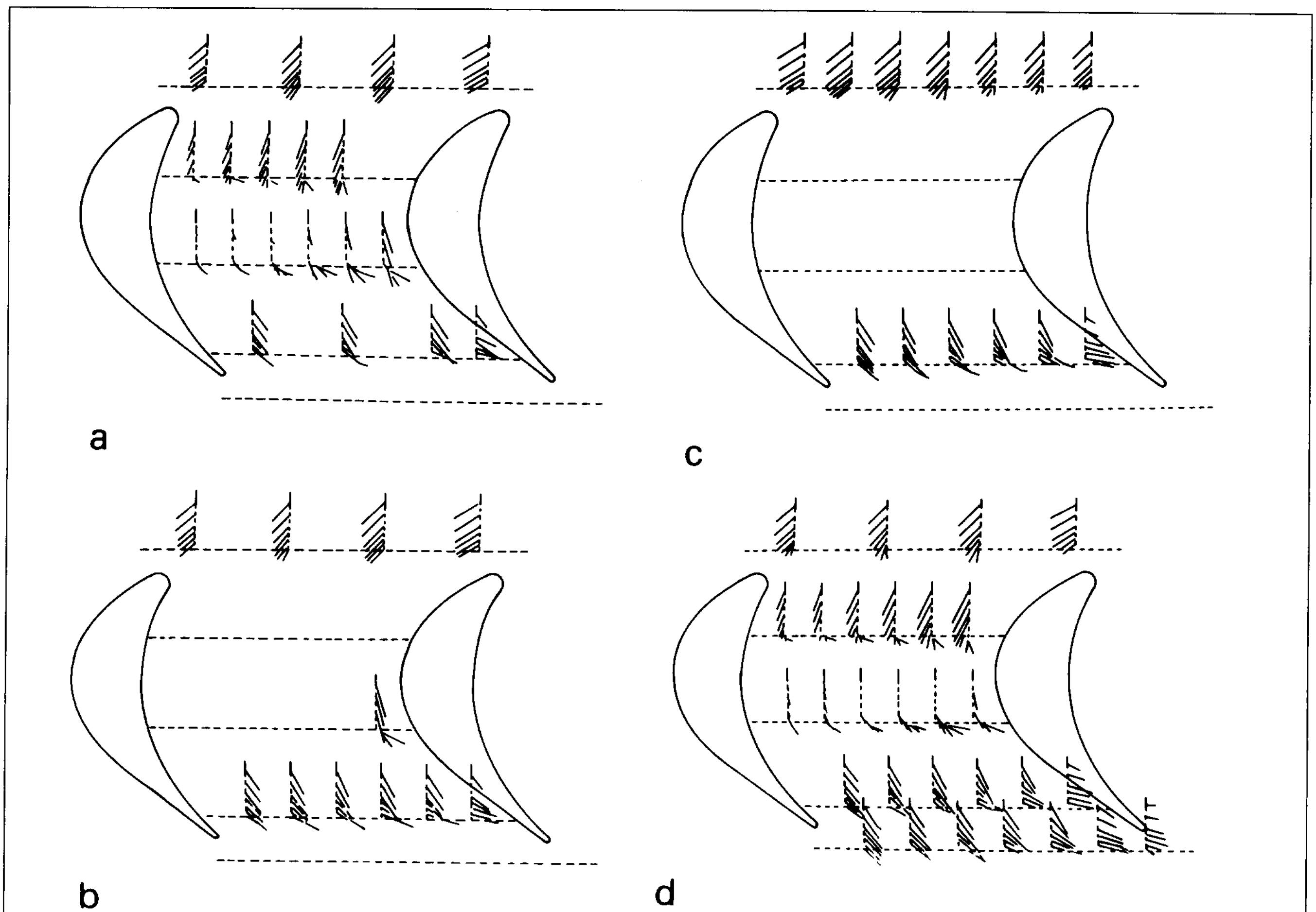


Fig 12 Three-dimensional cascade flow[13] *(a) high Re, no skew (b) lower Re, intermediate skew (c) lower Re, no skew (d) lower Re, high skew*

covery that gives new understanding and provides the basis for an improved model in the flow calculation methods.

There remain a number of fundamental problems in turbomachinery flows which have yet to be understood and modelled correctly. They include:

1. The nature of the boundary conditions on pressure downstream of twisted blade rows.
2. Accurate descriptions of the three-dimensional annulus wall boundary layers as they develop from blade row to blade row.
3. The behaviour of mixed supersonic and subsonic flows at entry to turbomachines.
4. The radial flows developed on the blade rows of rotors and stators and their interaction with the annulus wall boundary layers at the casing and hub.

These and other related problems in turbomachinery fluid mechanics will continue to provide plenty of scope for fundamental research in the next few years. The emphasis will be on obtaining a better understanding of the flow, so that the mathematical modelling can be improved and more efficient machines developed.

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BOOK REVIEWS

Prediction of Turbulent Reacting Flows in Practical Systems

T. Morel (Ed)

This slim volume contains three papers presented at the ASME's Fluid Engineering Division meeting at Boulder, Colorado, in June 1981. It follows ASME's recent trend of binding together collections of conference papers rather than issuing each manuscript as a separate preprint. This approach has a number of economic and logistic advantages for the authors, the readers and the Society itself. The papers, each in the nature of a survey article, address three overlapping aspects of the problem of calculating turbulent reacting flows of practical interest.

The contribution by Westbrook and Dryer, an entirely discursive article, considers chemical-kinetic aspects of the problem. The article by Jones and Whitelaw considers a wide range of topics at rather uneven depths: the section on numerical solution methods is fairly superficial, while the discussion on turbulence and the way it impinges on the problem of chemical reaction is much more authoritative. There would, one might suppose, be a strong interlinkage between these first two articles. One gets the impression, however, from the Jones–Whitelaw contribution that the questions of complex chemistry addressed by the Westbrook–Dryer paper are of only academic significance, while for their part, the latter authors discuss chemical reaction models in isolation from the questions of turbulence. This polarity of outlook, while reflecting the different background disciplines of the research workers concerned, is one that needs to be neutralised if many of the important problems of turbulent combustion are to be solved.

The final article by Harsha focuses on applications. His examples range from simple jets to recirculating flows and practical combustors. Through no fault of the reviewer, such surveys tend to produce a too favourable impression of the status of calculation methods, for his source material (ie the technical literature) is biased towards success: editors and authors share a disinclination to publish papers showing terrible agreement between experiments and computation. Overcoming this aversion to failure would be a further important step towards maturity in the understanding of turbulent reacting flows.

Collectively the articles give a timely, if ephemeral, snapshot of the current (or, rather, 1980) state of research in turbulent combustion. The volume is inexpensive and should be bought by anyone currently wishing to get more deeply into the subject. More than 180 papers are cited in the reviews and this alone is worth the cover price. It makes less sense as a library purchase, as the useful half life of the volume is probably not greater than two years.

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An Introduction to Thermodynamics

J. P. Todd and H. B. Ellis

The authors claim their material to be aimed primarily at Engineering Technologists in training. The topics are clearly presented and aimed at a level no higher than a first year undergraduate course in Engineering. The level of ability to which the book is suited is intermediate; it is certainly not for the academic, but not strictly for the applied engineer, even if there are many helpful, practical illustrations. The questions at the end of each chapter and selected answers will be appreciated by the student reader. Judged alongside a standard undergraduate text such as Rogers and Mayhew, this work covers a wide range of topics but in considerably less depth.